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MEASUREMENT OF INTENSITIES IN THE VACUUM SPECTRAL REGION

Ye. Ya. Shreyder

ABSTRACT

22619

Methods of performing absolute and relative intensity measurements in the vacuum ultraviolet are discussed. Reasons for difficulties in performing calibrations, and the advantages of use of the synchrotron for comparison of radiation are explained. Drawbacks and advantages of continuous calibration of the entire system are stated, and preference of open photomultipliers and gas-filled ionization chambers are included.

Introduction

The methods of measurement of intensities in the vacuum region of the spectrum have begun their development in the last three years chiefly in connection with three directions of scientific research: (1) cosmic astrophysics; (2) study of the radiation of hot plasmas; (3) photoionization of atoms and molecules.

In carrying out absolute energy measurements, depending upon the problem under consideration, it is necessary to measure the following quantities:

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*Numbers given in the margin indicate the pagination in the original foreign text.

(1) absolute intensity of a spectral line;[1] (2) integral brightness of a spectral line; (3) spectral brightness of the source; (4) light flux entering the spectral instrument.[2]

All these quantities are interrelated and may be determined if one of them has been measured and the geometrical parameters of the instrument are known (ref. 1).

We shall consider the methods of intensity measurement in the spectral range of 100 to 2000 Å.

The methods of homochromatic photometry are comparatively simple and do not require a preliminary calibration of the entire recording system, i.e., of the spectral instrument and radiation detector.

The measurement of absolute intensities and the problems of heterochromatic photometry are quite complex and can be solved by two fundamentally different methods. The first method is based on the use of standard light sources having a known energy distribution. The second method consists in a preliminary determination of the transmission coefficient of the spectral instrument and of the detector sensitivity.

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[1] We shall define the absolute intensity of a spectral line as a quantity proportional to the integral power of radiation emitted by a unit volume of the source and associated with the entire width of the line.

[2] An integral flux is defined for a line, whereas for the source of a continuous spectrum the flux is defined for a certain spectral interval.

Both methods of measurement can be explained by the following formula

$$i = K_1(\lambda)K_2(\lambda)J(\lambda) \qquad (1)$$

where i are the readings of the instrument (giving, for example, the measured current in the circuit of the amplifier of the PEM, the number of ions per second recorded in the iбnization chamber, etc.); $J(\lambda)$ is the light flux entering the spectral instrument; $K_1(\lambda)$ is the transmission coefficient of the spectral instrument; $K_2(\lambda)$ is a coefficient characterizing the sensitivity of the detector and indicating the magnitude of the signal per quantum of incident radiation. Thus, for example, in the case of an ionization chamber this coefficient depends on the photoionization quantum yield of the gas filling the chamber, on the cross section of radiation absorption in this gas, and on a number of other factors.

First method. In the presence of a standard source of known spectral brightness, one can find the light flux entering the spectral instrument (ref. 1). Measurement of the signal at the exit from the instrument makes it possible to determine the product of the coefficients $K_1(\lambda)K_2(\lambda)$ for various wavelengths. The entire recording system is thus calibrated (spectral instrument plus detector).

Subsequently, we shall discuss the methods of creating standard light sources for the vacuum region of the spectrum (S.2 -- 5). The standard sources which we have described become such sources only when simultaneous measurements are made in the visible region of the spectrum. Only the synchrotron (S.5) can be regarded as a standard source in the usual sense of this term.

Second method. Both coefficients entering into formula (1) are determined independently from each other. If the transmission coefficient of the

3

instrument $K_1(\lambda)$ is known (see S.6), the problem of measuring the light flux entering the spectral instrument amounts to measuring the light flux at the exit from this instrument (see S.7). For absolute measurements, coefficients $K_1(\lambda)$ and $K_2(\lambda)$ should both be known. For relative measurements, it is sufficient to know how these coefficients vary with the wavelength.

The coefficient $K_2(\lambda)$ is determined by comparison with a standard detector.

To measure relative intensities, the second method is very convenient in cases where a nonselective detector is available.

1. Homochromatic Photometry

Homochromatic photometry in the vacuum region of the spectrum in photoelectric recording is no different from ordinary photoelectric measurements. Any detector (see S.7) sensitive in the spectral interval under consideration and having a linear characteristic can be used for this purpose.

In photographic recording, the problem of the method to be used in the plotting of the characteristic curves arises. The most widely accepted methods of plotting the characteristic curves, involving the use of step attenuators, are not suitable, since on the one hand, in the majority of cases the instruments used in the vacuum region of the spectrum are astigmatic, and on the other, it is difficult to select the materials for making the attenuator that are transparent in this region.

In plotting the characteristic curve, the method of grids is frequently employed, but the disadvantage lies in the fact that the grid must be placed directly in front of the slit; in addition, every point on the characteristic curve is obtained by a separate exposure. When the grid method is used, extremely high requirements must be met with respect to the stability of the light source.

There exists a whole series of other methods of plotting characteristic curves.

Use may be made of known intensity ratios in the multiplets. Thus, for example, in the case of the lines of light atoms, which have a small number of outer electrons, one can expect the intensity rule to be obeyed for the L-S bond, and the intensity ratio of the components of the multiplet is then calculated theoretically. For greater reliability, considering possible deviations from the theoretical ratio as well as distortions introduced by reabsorption, it is best to perform a preliminary check by any other methods (see below) and then to use only the intensity ratios within the multiplet. Thus, for example, Krasnova and Yakovleva (ref. 2) found the ratio of line intensities within the multiplets of nitrogen $2p^3 {}^2P - 3s^2P$ and $2p^3 {}^2D - 3s^2P$; Gladushchak et al. (ref. 3) checked the intensity ratio of a series of lines /2091 of Al III and Si IV and found, contrary to the results of Kisiel (ref. 4), that this ratio is in rigorous agreement with the theory. A similar method is proposed in ref. 5, the calibration of the plate being made on the basis of the relative line intensities in the multiplets in the spectral region of 200-500 Å. It is necessary (before using this method) to make sure that reabsorption is absent (ref. 6). Furthermore, it should be pointed out that this method is more reliable if the components of the doublet have a common upper, not lower level; otherwise, the method can be applied only after a preliminary check for the presence of statistical distribution of the atoms or ions over the energy levels.[1]

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[1] Here and subsequently, the term statistical distribution will refer to a distribution of atoms or ions over the energy levels which is proportional to their statistical weights.

For this reason, it is our view that the multiplet method must be considered merely as an auxiliary method having no independent significance, and applicable only after a preliminary check by another method. An improved variant of this method is the measurement of intensity within the multiple by means of a linear detector, for example, a PEM, and the measured (not theoretical) ratio then makes it possible to find the slope of the characteristic curve (ref. 7). Other methods are also applicable. For example, to plot the characteristic curve photoelectrically, Pery-Thorne and Garton proposed to establish the dependence of the spectral line intensities on the current intensity in the discharge and then to take the pictures in the presence of these currents (ref. 8). The relative intensities will then be known on various pictures, and this will replace the taking of pictures with a step attenuator. Obviously, this method is applicable if the manner in which the intensity varies as a function of any other parameter of the electric circuit, e.g., capacitance, is established (ref. 7). By using this method, it is possible to tolerate errors due to fluctuations in the intensity of the light source.
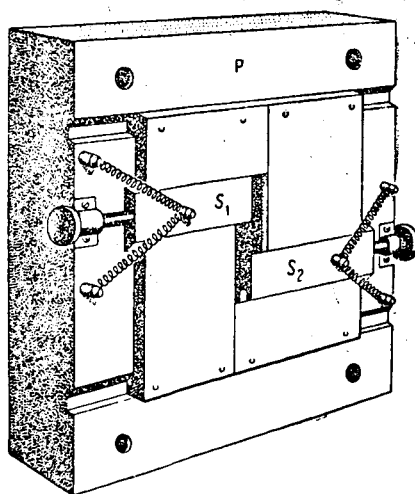

Figure 1. Mask applied on slit to divide the beam.

One of the methods of calibrating spectral instruments (see S.   2, 3) is based on the simultaneous recording of pictures in the vacuum and visible regions of the spectrum. By recording lines having a common upper level and located in different regions of the spectrum by means of various spectral instruments, one can change the intensity of both spectral lines by changing the conditions of the discharge. By taking measurements in the visible using a step attenuator, one can determine the factor by which the intensity of the spectral line changes from picture to picture in the vacuum region. This makes it possible to plot the characteristic curve.

To determine the contrast coefficient of a photographic emulsion, Johns (ref. 7) suggested the use of a composite mask for the slit (Fig. 1), making it possible to separate the beam entering the spectrograph into three equal parts; the central parts illuminates the entire grating, and each of the external parts illuminates only the opposite halves of the grating. The picture has the appearance shown in Fig. 2. If all three parts of the line are measured photometrically, the average density of the outer portions of the lines and the density of the central portion make it possible to find the slope of the characteristic curve. The method is particularly suitable for measuring line half-widths, since a half-width is measured at points corresponding to one-half the intensity at the peak.

The Johns method (ref. 7) may lead to significant errors if the reflection coefficient of the grating changes appreciably along its surface.

Finally, the most common method is based on the fact that a photoemulsion sensitized with a luminophor has a constant contrast coefficient for all wavelengths which depends on the region of luminescence of the given luminophor
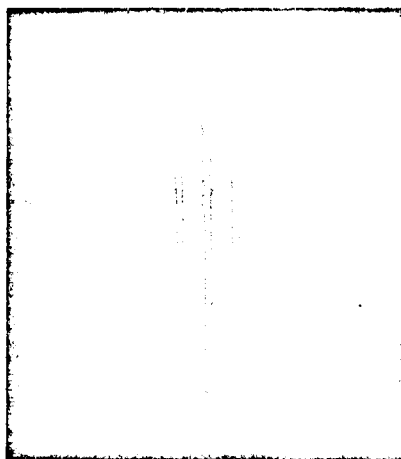
Figure 2. Spectral lines with edges attenuated by a factor of 1/2.

(refs. 9-11)[1]. In order to plot the characteristic curve, it is necessary to make blackening marks for the region of the spectrum to which the usual photometric technique is applicable; in particular, it is convenient to carry out the measurements with the aid of gratings or step attenuators in the wavelength region of 2200-2000 Å (refs. 2-3). The light source used may be a hydrogen lamp, and the pictures are taken on two separate films; both films are cut from the same sheet, are sensitized in the same manner, and are simultaneously developed. This method is sufficiently simple and reliable.

Homochromatic photometry in the vacuum region of the spectrum is used in all investigations involving measurements of line half-widths, measurements of absorption cross sections, in spectrum analysis, and in other investigations.

2. Calculated Relative Intensities as the Basis for the Method of Heterochromatic Photometry

The ratio of the intensities of two spectral lines J_1 and J_2 located in the vacuum region of the spectrum can be easily found from the known intensity ratio

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[1] It is assumed that the radiation is completely absorbed by the luminophor.

of the lines in the visible, J_3 and J_4, provided that the lines J_1 and J_3 have a common upper level and the lines J_2 and J_4 have another common upper level [Fig. 3 (refs. 12-14)]

$$\frac{J_1}{J_2} = \frac{J_3}{J_4} \frac{A_1}{A_2} \frac{A_4}{A_3} \frac{\lambda_2}{\lambda_1} \frac{\lambda_3}{\lambda_4},$$ (2)

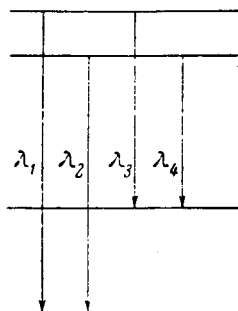where A is the transition probability and λ is the wavelength.

Figure 3. Energy level diagram.

By selecting such pairs over the entire spectral region, one can find the dependence of the effective quantum yield of the entire unit (spectral instrument plus radiation detector) on the wavelength. If the spectral characteristic of the detector is known, by using this method one can find in relative units the transmission coefficient of the spectral instrument for various wavelengths.

The method is applicable when the following conditions are observed: (1) absence of reabsorption (optically thin layer); (2) the transition probabilities of the lines with a common upper level should be known; (3) if the levels of the hyperfine structure are not resolved, the distribution over the energy levels should be proportional to the statistical weights.

In order to calibrate the instrument, one must have a set of spectral /2093 lines covering the entire working region of the spectrum. The spectrum is recorded simultaneously with two spectral instruments, and special steps are

9

taken to make sure that emission from the same portion of the source enters both instruments. Hinnow and Hoffmann (ref. 13) performed the calibration by using the lines He 231, 232, 234, 237, 243, 1085, 1640 $\overset{\text{o}}{\text{A}}$ and H 937, 950, 972 and 1026 $\overset{\text{o}}{\text{A}}$. For all these lines, pairs were selected in the visible which had upper levels in common with the lines used for the calibration. An attempt was made to use the He 537 $\overset{\text{o}}{\text{A}}$ line having a common upper level with the He 5015 $\overset{\text{o}}{\text{A}}$ line for the calibration, but an optically thin layer could not be obtained at any pressures for this line. The light source in this work was a tube with a cooled hollow cathode. The helium pressure in the discharge tube was selected so as to avoid any appreciable absorption beyond the limit of the series. The effectiveness of the whole unit $S(\lambda)$ (as a function of the wavelength) was determined from the following formula where

$$R(\lambda) = I(\lambda)S(\lambda)x, \tag{3}$$

where $I(\lambda)$ is the total intensity at the entrance slit in photons, cm^2/sec; $R(\lambda)$ is the measured photocurrent; and x is the slit width. Two instruments were calibrated: one with grazing incidence and the other assembled according to the Sei-Namiok design (ref. 15). The main source of error in this cali-bration technique is the fact that one cannot be certain that there is a statistical distribution of the atoms over the energy levels; this becomes important, since the fine-structure levels of H and He II are not resolved.

The authors evaluate in detail the possibility of significant deviations from equilibrium levels and come to the conclusion that such deviations cannot take place if $N_e > 10^{13} CM^{-3}$ for He II and $N_e > 10^{12} CM^{-3}$ for H. Since in the hollow cathode the electron concentrations may turn out to be considerably lower, this may result in substantial errors. The use of such hot sources as the Stellarator (ref. 13) or Zeta (ref. 14) has been more successful in this regard.

The method proposed by Griffin and McWhirter (ref. 14) is similar to the one discussed above.

Gladushchak et al. (ref. 3) calibrated a vacuum spectrograph with the lines of Al III and Si IV excited in a low-voltage vacuum spark (ref. 16). The transition probabilities of the lines of Al III and Si IV can be readily calculated from the tables of Bates and Damgaard (ref. 17). The use of these transition probabilities introduces a certain additional error into the calibration of the spectral instrument, but since the fine-strucutre levels are resolved in this case, it is not necessary to assume the presence of a statistical distribution. As was confirmed in several studies, the determination of the line transition probabilities of elements of the isoelectronic series of lithium and sodium by means of the Bates-Damgaard tables is sufficiently reliable (refs. 18, 19). The discharge took place between electrodes made of carbon, aluminum and Silumin. The absence of reabsorption was checked by means of the ratio of line intensities in the doublets. The calibration was made in the spectral region from 2200 to 450 Å. The coefficient $K(\lambda)$ was determined experimentally from the formula

$$\left(\frac{J_1}{J_2}\right)' = K(\lambda)\frac{J_1}{J_2},$$ (4)

where J_1/J_2 is the ratio of the intensities in the source; $\left(J_1/J_2\right)'$ is the recorded intensity ratio corresponding to the true ratio if the detector and spectral instrument are not selective. The coefficient $K(\lambda)$ [like $S(\lambda)$ in the preceding work] depends on the efficiency of the grating and on the properties of the sensitizer[1]. The method was used to calibrate a normal-incidence spectrograph.

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[1]The value of the coefficient $K(\lambda)$ may be affected by the astigmatism of the instrument and by defects in positioning.

11

The coefficient $K(\lambda)$ in the region of 2200 to 450 Å decreases by a factor of 1000.

Thus, both of the studies discussed here (refs. 3, 13) are different variants of the method based on the use of calculated transition probabilities. The advantage of this method over the method involving the determination of grating efficiency and spectral characteristic of the detector with the aid of a different unit lies in the fact that, on the one hand, the grating is calibrated under the same conditions under which it is used and, on the other hand, it is not necessary to determine the characteristic of the radiation detector. In the above method, the unit as a whole is calibrated, i.e., the calibration includes both the sensitivity of the PEM and the quantum yield of the luminophor (if a closed-type photomultiplier is used). An important drawback of this method is that the calibration is made for individual points, not for the region of the spectrum as a whole. This drawback is particularly perceptible if an instrument with the concentration of light in a definite direction is being calibrated.

In addition to the method of calculated transition probabilities, the method of experimental determination of the intensities of various multiplets with a common upper level may also find applications. Krasnova and Yakovleva (ref. 2) determined the intensity ratio of the multiplets of nitrogen λ 1492 and λ 1742 Å. Having such a set of experimentally measured multiplet intensity ratios, one can perform the calibration. The inconvenience of the method is that it can be used only after preliminary measurements by means of an instrument calibrated by another method. The authors of the article indicate that the intensity ratio of both multiplets can be calculated by assuming the presence of an L-S bond.

3. Use of the Radiation of a Thin Layer for the Creation of Standards in
   Vacuum Region of the Spectrum

The method of heterochromatic photometry presented above is at the basis of the method of creating sources of standard radiation. Standard radiation can be given off by any source whose spectrum contains a pair of lines with a common upper level, one of these lines being located in the vacuum region of the spectrum.

The intensity of the shortwave component (J_1) can be found by measuring the intensity of the longwave component (J_3) and if the transition probabilities A_1 and A_3 are known

$$J_1 = J_3 \frac{A_1}{A_3} \frac{\lambda_3}{\lambda_1} \cdot \qquad (5)$$

Formula (5) is valid in the absence of reabsorption.

Monochromatic radiation corresponding to the wavelength λ_1 may be considered as the standard. The recording of standard radiation (J_1) and radiation in the visible region (J_3) should be carried out simultaneously. The brightness of the source in the direction of both spectral instruments should be the same.

If a sufficient number of such pairs which occupy with relative uniformity the entire vacuum region of the spectrum are selected and measured, the problem of creating a standard source for the entire vacuum region will be solved. Sources suitable for the creation of such "standards" have been discussed in several studies (refs. 13, 20, 21).

Van Eck et al. (ref. 20) determined the absolute intensity of the He λ 537 $\overset{\circ}{A}$ line from the intensity of the λ 5015 $\overset{\circ}{A}$ line. Self-absorption was successfully avoided owing to the Doppler broadening of the λ 537 $\overset{\circ}{A}$ line.

13

The absolute intensity of the lines in the Lyman series of hydrogen was determined from the absolute intensity of the lines in the Balmer series. The measurements were made in a "hollow cathode" on the Zeta unit and on the stellarator (refs. 13, 14); the line intensities of ionized helium (231-237 Å) were measured in a "hollow cathode," and the intensity of the lines of Al III were determined in a low-voltage vacuum spark (ref. 21).

The use of lines of hydrogen and ionized helium for the creation of standards in the vacuum region may lead to substantial errors due to the absence of a statistical distribution of the atoms over the energy levels (see above).

The accuracy of the determination of standard radiation intensity depends on the photometry errors and errors in the determination of the transition probabilities. We shall enumerate the wavelengths (in Å) of those spectral lines which can be used as standards in the vacuum region of the spectrum: $\lambda\lambda$ 2213 (AlIII), 1727 (SiIV), 1640 (HeII), 1352 (AlIII), 1085 (HeII), 1026 (H), 972 (H), 950 (H), 937 (H), 695 (AlIII), 560 (AlIII) 456 (Si IV), 237 (HeII), 234 (He II), 232 (HeII), 231 (HeII).

Apparently, the lines of Be II, Mg II, B III and P V are also suitable for these purposes, but nobody has verified the possibility of their use.

4. Absolutely Black Radiation as a Standard in the Vacuum Region of the Spectrum

The problem of the creation of standards in the vacuum region of the spectrum was solved in refs. 22 and 23 in a different manner. The intensity standard in the vacuum region can be the radiation of individual spectral lines if it corresponds to the radiation of an absolute black body at the temperature of the source. Garton and Foster (ref. 22) suggested the use of

the radiation of an optically thick arc at temperature $T = 12436^{\circ}$ K, current

intensity of 50 Å, channel diameter of 8 mm, and $P = 1$ atm. He calculated the

intensity of the line L_{α} and OI (1302 Å). The problems of creating such a

light source are discussed in more detail in ref. 23, where use was made of an

arc burning in argon. The plasma was obtained in a cascade arc developed by

Maecker (ref. 24). The arc was stabilized with walls. The channel of the arc

was formed inside perforated water-cooled copper plates. As is evident from

Fig. 4, the distance between the plates is constant and is reduced only between

the second and third pairs of plates (2 mm). The electrodes are made of

graphite, and the washers are insulated with teflon rings. The arc is struck

by means of a thin copper wire which connects the cathode to the anode. Gas

enters into apertures 1, 2, and 3,   and the plasma is formed on both

sides of the constriction. Owing to the large distance between the third and

fourth washers (beginning with the fourth washer), a homogeneous plasma of

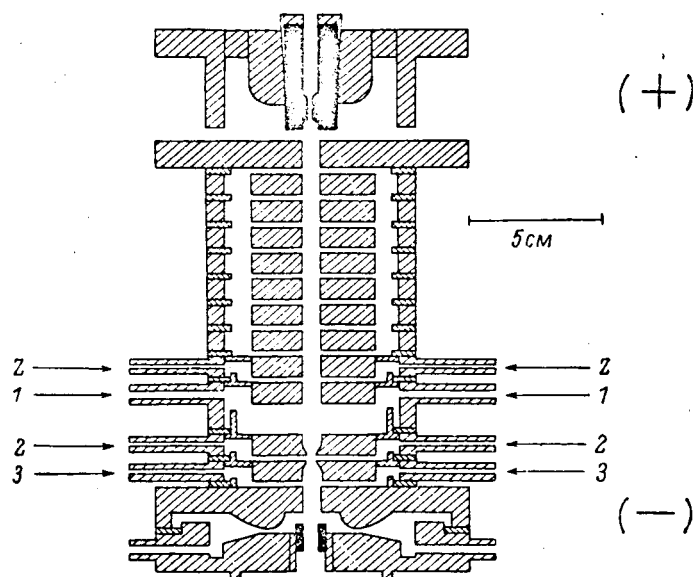constant temperature is obtained. The added gas (hydrogen) is introduced into

Figure 4. Diagram of cascade arc.

aper ture Z in amounts which do not cause a change in temperature; the hydrogen concentration should be sufficient so that its radiation, when observed along the axis of the arc corresponds to the radiation of an absolute black body. The temperature was determined from the Saha formula which, as we know, contains the electron concentration. The latter was measured from the Stark broadening H_β. Special experiments showed that the arc temperature and hydrogen concentration are constant in that part of the discharge where hydrogen glows; hydrogen does not reach those parts of the arc where the temperature changes because of the counterflow of the gas. One can assume, therefore, that the whole layer of gas in which hydrogen is excited is homogeneous. After a

/2096

homogeneous, glowing column was formed, it was necessary to create conditions which would permit the recording of this radiation by means of a vacuum spectrograph without absorption. To this end, a vacuum chamber with differential pumping was used whose construction is apparent from Fig. 5. The diameter of of the source was 0.9 mm, and that of the others, 1.3 mm. All the diaphragms
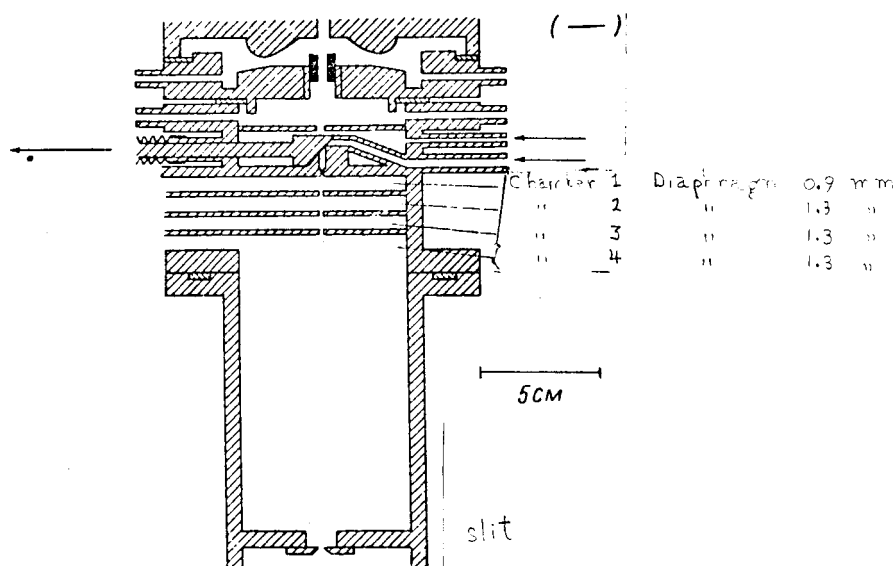

Figure 5. Vacuum chamber with differential pumping.

16

were located on the optical axis at a distance of 8 mm from one another. Each

chamber was evacuated separately. At a slit width of 0.15 mm it was verified

that in the vicinity of L_α (1216 Å) the radiation was homogeneous over a

distance of 10 Å. Thus, in the range of wavelengths of 1211-1221 Å, it is

possible to obtain a homogeneous radiation which corresponds to the radiation

of an absolute black body at 11900° K. The light flux entering the spectrograph

and corresponding to a unit wavelength interval may be calculated from the

formula

$$\Phi = \frac{FS}{a^2} B_\lambda(T),$$

(6)

where F is the area of the entrance diaphragm; S is the area of the slit; a is

the distance to the slit of the spectrograph; B_λ is the brightness of the source.

Using this source, one can similarly obtain standards for the radiation of

other gases.

Grimm (ref. 13) chose the same source, and suggested the use of the radi-

ation of an optically thick layer of helium and hydrogen in a shock tube.

To create a radiation standard in the vacuum region of the spectrum, it

is apparently easy to use a glow discharge in inert gases. Thus, Yakovlev

(ref. 25) points out that when the length of the capillary in the lamp which

he constructed was increased, the intensity of the resonance lines of xenon

did not increase. This is possible only if the capillary of this lamp observed

along its axis radiates as an absolute black body. In order to calculate the

radiation intensity of the resonance lines, it is necessary to know the

temperature corresponding to the radiation of each of these resonance lines.

To do this, it is necessary to determine the population at the levels

17

P_4 and P_2 (Fig. 6). According to Boltzmann's formula

$$N_2 = \frac{g_2}{g_0} N_0 e^{-\frac{h\nu}{kT}},$$

(7)

where N_2 is the population of the upper level; N_0 is the population of the ground level; ν_2 is the frequency of the resonance line; g_2 and g_0 are statistical weights.
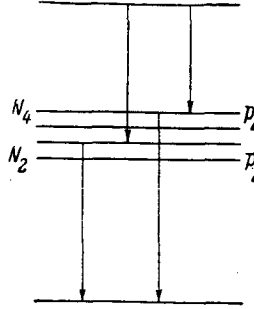

Figure 6. Diagram of transitions in inert gases.

The spectral radiation density may be found from the approximate Wien formula

$$\rho(\lambda_2) = \frac{8\pi hc}{\lambda_2^5} e^{-\frac{hc}{\lambda_2 kT}},$$

(8)

where λ_2 is the wavelength of the resonance line.

Using formulas (7) and (8), one can show that

$$\rho(\lambda_2) = \frac{8\pi hc}{\lambda_2^5} \frac{g_0 N_2}{g_2 N_0}.$$

(9)

Similarly, we find the expression for $\rho(\lambda_4)$.

Thus, to determine the spectral radiation density, it is necessary to know the populations of levels p_4 and p_2 (N_4 and N_2). They can be determined by the method of anomalous dispersion of reabsortion if one knows the oscillator forces of lines whose lower levels are p_4 and p_2.

The transition probabilities for argon lines lying in the visible apparently have been reliably determined (ref. 26), and calculated for helium (ref. 27), whereas reliable

18

calculations or measurements of absolute transition probabilities are still lacking for krypton, xenon and neon. When the oscillator forces of the lines of inert gases are determined, a series of standards will be added: Xe 1470 Å, 1295 Å, K 1235 Å, 1165 Å, Ar 1067 Å, 1048 Å, Ne 744 Å, Ne 736 Å, He 584 Å, 537 Å. For observations of the radiation of heavy inert gases, lamps with lithium fluoride windows can be constructed. For helium and neon, the lamp should be open, and therefore, in order to avoid the self-absorption of absolute black body radiation, it is necessary to construct a chamber with differential pumping; /2098 this complicates the design of the lamp considerably. The "standards" used can also be the lines of the heaviest inert gas radon (1786 and 1452 Å).

5. Synchrotron and Secondary Radiation Standards in the Vacuum Region of the Spectrum

The synchrotron is a light source which should play a considerable part in vacuum spectroscopy (refs. 28, 29). Its radiation can be precisely calculated both in relative and in absolute units. The instantaneous power P(λ, t) radiated in all directions may be found from the following formula

$$P(\lambda,\ t) = \frac{3^{5/2}}{16\pi^2}\left(\frac{e^2c}{R^3}\right)\left(\frac{E}{m_0c^2}\right)^7 G(y), \tag{10}$$

where R is the orbit radius and E is the energy. G (y) can be found from the formula

$$\tag{11}$$

$$G(y) = y^3 \int_y^\infty K_{5/3}(\eta)\, d\eta,$$

$$\text{where} \quad y = \frac{\lambda_c}{\lambda}, \quad \text{and}$$

$$\lambda_c = \left(\frac{4\pi R}{3}\right)\left(\frac{m_0c^2}{E}\right)^3 \tag{12}$$

19

$K_{5/3}(\eta)$ is a complex combination of Bessel functions of an imaginary argument, and the integral entering into formula (11) can be integrated numerically.

To determine P (λ, t), it is necessary to know energy E and wavelength λ; first for a given energy E, λ_c is calculated, then G(y) is found for various wavelengths from the graph shown in Fig. 7. From Formulas (10) and (12) it is apparent that P (λ) $\sim E^7$ and $\lambda_c \sim E^{-3}$. It can be readily shown (Fig. 7) that the width of the distribution at points corresponding to one-half the intensity is 0.84 λ_c. This means that at low energies the intensity changes little with changing wavelength. This may be readily verified by examining Fig. 8.

$$P(\lambda) = \text{const} \left(\frac{E}{m_0 c^2}\right)^7 G(V). \quad 1 - 240, \quad 2 - 260,$$
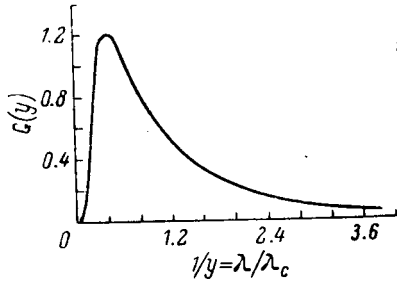$$3 - 280, \; 4 - 300, \; .5 - 320 \; \text{Mev.}$$

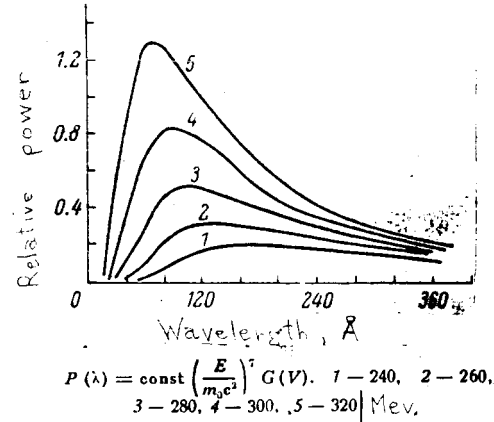Figure 7. Spectral distribution for instantaneous power of synchrotron.

Figure 8. Spectral distribution for various energies of synchrotron.

By calculating the average energy radiated during an oscillation period, one finds that the character of the change in energy as a function of wavelength remains the same as for the instantaneous power. The authors verified the theoretical formulas experimentally. The initial check was carried out in the wavelength range from 2800 to 4800 Å; the results of the check are shown in Fig. 9. In the vacuum region of the spectrum, such a check is much more complicated, since it is necessary to know the efficiency of the grating distribution over individual orders of magnitude (ref. 30). The check was made in the spectral region from 60 to 450 Å by means of a grazing-incidence

instrument (the dispersion varies from 0.7 to 1.8 Å/mm). As a result of the

check, points were obtained which are shown on a curve (Fig. 10). To check the

theory, the energies corresponding to one Ångstrom unit at a given wavelength

for 321 and 233 Mev were compared with one another. The comparison was made

in the wavelength range from 170 to 250 Å. The energy ratio was compared with

the theoretical one. The close agreement between the theory and experiment

may be regarded as a confirmation of the theory. All the measurements were

made photographically.

This work is interesting not only because it shows the possibility of

using the synchrotron as a standard light source, but also because it gives

detailed recommendations concerning the technique of photographic measurements
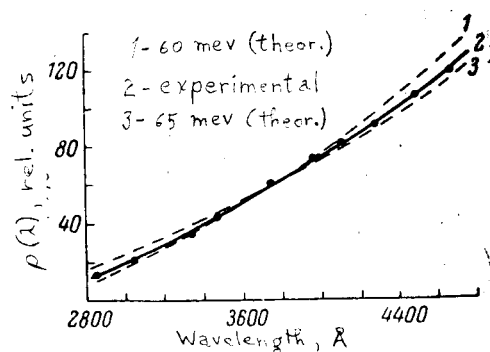
in the vacuum ultraviolet.

Figure 9. Comparison of the theoretical spectral distribution of the average power of synchrotron with the experimental one at an energy of 60 mev (λλ 2800-4600 Å).
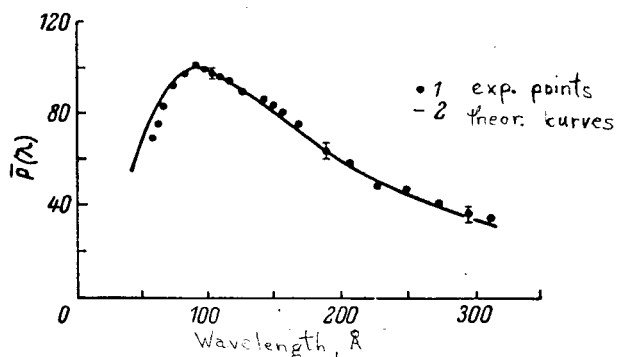

Figure 10. Comparison of the theoretical spectral distribution of average power of synchrotron with the experimental one at an energy of 321 mev (λλ60-350 Å).

Using synchrotron radiation, one can calibrate such light sources as the

hydrogen lamp (refs. 31, 32) and a condensed glow discharge in inert gases

(ref. 33). The hydrogen lamp gives off a continuous radiation up to 1650 Å,

and a band spectrum up to 900 Å. The helium continuum extends from 4000 to 600 Å. These radiation sources can be   ed as secondary radiation standards. They can be calibrated not only by means of a synchrotron, but also by recording the irradiation with instruments and detectors of known spectral sensitivity; a nonselective detector is best suited for this purpose. A technique of such type of measurements has been perfected in the visible and near ultraviolet (ref. 34).

This method of absolute calibration proposed by Garton (ref. 13) stands somewhat apart from the others. It is based on the fact that light radiated by a condensed discharge in helium (pressure of the order of a few millimeters of mercury) passes through an absorption chamber (p ∼ 0.1 mm) before entering the spectrograph. The change in intensity is measured as a function of the pressure in the absorption chamber. From the known photoionization cross section one can find the number of photons which have left the beam and relate it to the change in the intensity of the helium line.

6. Determination of the Transmission Coefficient of a Spectral Instrument

The transmission coefficient of a spectral instrument or its efficiency can be determined by means of an additional monochromator (refs. 35, 36). In visible and ultraviolet, these measurements do not present any particular difficulties; the intensity of light which has passed through the first mono- chromators is measured, making it possible to determine the transmission coefficient of the second instrument; in absolute measurements, one must know the absolute value of the transmission coefficient of the monochromator, and in relative measurements this value may be measured in relative units for different wavelengths. In the vacuum region, such measurements involve con- siderable difficulties, and for this reason it is usually preferred to use an

additional monochromator for determining separately and at various incidence
angles the efficiency of the diffraction grating of the instrument being
calibrated. The difficulties involved in the calibration were successfully
overcome in a series of experimental devices (refs. 37-40). The efficiency of
the grating was studied as a function of the wavelength, angle of incidence,
coating, etc. All these measurements showed that in a whole series of cases
the losses were very high and the efficiency was less than 1%. The grating
efficiency may vary appreciably in different parts of the grating. For short
waves, the efficiency of glass gratings is greater than that of aluminum-coated
gratings. When the incidence of light is normal on the grating, the efficiency
declines very sharply in the shortwave region, and for this reason, instruments
with normal incidence of light are not employed for wavelengths of less than
500 Å. The properties of a grating were studied very thoroughly by Kulikov and
Nikitin (ref. 39); it should be noted that at large angles of incidence (grazing
incidence) the grating efficiency depends little on the wavelength.

On the other hand, at small angles of incidence, this dependence is pro-
nounced. The coating of an aluminized grating by various films, particularly
MgF_2, raises the reflection coefficient of the grating considerably (ref. 41).
This is due to the fact that the MgF_2 layer protects aluminum against oxidation,
and the oxide layer markedly decreases the reflection coefficient of the grating
(ref. 42). The reflection coefficient of a glass grating in the soft X-ray (ref. 43)
region increases when a gold coating is applied.

We shall describe one of the procedures used for measuring the efficiency
of a diffraction grating (Fig. 11) (ref. 40). As is evident from Fig. 11, an
attachment was made for the Sei-Namiok monochromator (ref. 15). The attachment
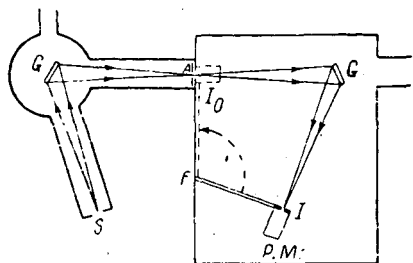consists of a rectangular housing in which are placed the grating, the

Figure 11. Diagram of setup for the
calibration of a diffraction grating

photomultipiler P.M., and a lever system permitting the rotation of the PEM

around F. When the photomultiplier is placed at point A, it is struck by all

of the light I_0 incident on the grating. If the PEM is placed at I, light

attenuated by reflection from the grating being calibrated will be recorded.

During the calibration, it is necessary that both gratings be in a position

such that the same wavelengths are present at the entrance and exit of the

attachment to the monochromator. The above-described method is also suited

for measuring the transmission coefficient of spectrographs.

In many astrophysical investigations, the transmissivity of a spectral

instrument was determined by measurements with two spectrographs (ref. 44).

Thus, in a study of ultraviolet solar radiation, the rocket spectrograph being

calibrated recorded the radiation of a line whose absolute intensity was

measured by means of a laboratory spectrograph. Measurements of the spectral   /2101

line density were made at the exit from the rocket instrument, and this

density was successfully correlated with the energy incident on the film. Thus,

knowing the energy incident on the instrument and the energy after passage

through the instrument, one can find the transmission coefficient of the

spectrograph. Tomboulian and Behring proposed a method for determining the

efficiency of a grating based on a comparison with a grating of known efficiency (ref. 45).

The use of a second spectral instrument may be avoided in calibrating a monochromator or spectrograph if the light source used is monochromatic (refs. 30, 46). Two measurements must then be made to determine the transmission coefficient of the instrument: one at the entrance slit of the instrument and one at the exit slit of the monochromator or in the plate-holder part of the spectrograph. This method was used by Sprague et al. (ref. 30) to determine the reflection coefficient of a grating in the soft X-ray region. The same method was used in ref. 46 to determine the efficiency of a DFS-6 spectrograph.

7. Measurement of Relative and Absolute Intensity at the Exit from the
   Spectral Instrument

In measuring the absolute and relative intensities of spectral lines radiated by a given light source, it is necessary to solve two independent problems: determination of the transmissivity coefficient of the spectral instrument and measurement of the light flux leaving the spectral instrument. In many cases, the second problem is of independent interest. We may be interested in the kind of energy that strikes the phosphor and the kind of energy which causes a chemical reaction; finally, in determining the quantum yield of the material of the photocathode, it is necessary to know the energy incident on the photocathode.

In relative measurement of intensity one can use a nonselective detector or a detector of known spectral characteristics.

In absolute measurements, it is necessary to know the absolute sensitivity of the detector.

(a)   Thermocuple

The thermocuple is a nonselective detector. A drawback of this detector
is its low sensitivity, so that in recording radiation by means of a thermo-
couple it is necessary to operate with very wide slits of the spectral
instrument, and this upsets the monochromaticity of the light flux. A tech-
nique of measurements by means of a thermocouple in the vacuum region of the
spectrum was developed by Packer and Lock (ref. 47).

The absolute calibration of a thermocouple is usually done in the visible.
To calibrate the thermocouple it is necessary to have a source in which the
distribution of radiated energy is known (for example, an absolute black
body). Such measurements can be made with sufficient reliability in the
visible. For more precise measurements in the vacuum region of the spectrum,
it is desirable to carry out the calibration by using a standard source for
this region of the spectrum, since the sensitivity of the thermocouple may
vary ever so slightly with the wavelength. Thus, for instance, in the region
of wavelengths from 400 to 1200 Å, the sensitivity of a thermocouple with gold
blackening may change by several percent because of a change in the photo-
electric quantum yield of gold. The photons responsible for the photoeffect
do not cause the thermocouple to heat up, and its sensitivity declines (ref. 48).

(b)   Photoelectric Detectors (ref. 49)

Photoelectric detectors may be divided into two groups: (1) closed-type
detectors and (2) open-type detectors.

The use of closed-type photoelectric detectors is based on the fact that   /2102
luminophors acted upon by extreme ultraviolet radiation emit light which
passes through the glass windows of the photomultiplier or photocell. As a
rule, a layer of luminophor is applied on the window of the photomultiplier.

Depending upon the luminophors employed, these detectors may be selective or nonselective. Among the numerous luninophors, it appears most convenient to use a layer applied by spraying saturated with an alcohol solution of sodium salicylate (refs. 48, 50-55). Numerous investigations have shown that freshly prepared layers of sodium salicylate have a constant quantum yield (within 10%) in the spectral region from 400 to 3400 Å. For wavelengths shorter than 1600 Å, an appreciable fatigue effect is observed for layers prepared several days before irradiation. The drop in quantum yield is particularly apparent in the shortwave region (refs. 48, 52).

The fatigue effect of a luminophor is apparently due to its interaction with various vapors inside the monochromator, for example, the formation of an absorbing layer on the phosphor itself, or possible chemical reactions (ref. 52).

When the phosphor is stored in air for a long time, no aging is observed (ref. 54).

A sharp decrease in quantum yield for sodium salicylate with decreasing wavelength was found in the work of Vasseur and Cantin (ref. 56). The quantum yield depends considerably on the thickness of the layer; a technique of applying layers of various thicknesses has been elaborated (ref. 57). For each wavelength, an optimum layer thickness can be found for which a maximum quantum yield is observed. The existence of such an optimum thickness is understandable if it is considered that no complete absorption of incident radiation is observed in a thin layer, whereas in a thick layer, even the light of the luminescence itself can be absorbed. In their experiments, the optimum layer thickness was found to be 2.3 mg/cm^2. The absolute quantum yield for the optimum layer thickness changed by a factor of three (from 28 to

82%) in going from 500 to 3000 Å. In thicker and thinner layers, the quantum yield does not change as sharply with changing wavelengths (by no more than a factor of two). Thus, the results of this work contradict the widely accepted notion that the quantum yield of sodium salicylate is constant. It may be that old layers have been investigated, and this explains the drop in the sensitivity of the luminophor in the shortwave region.

In this work, we first find the absolute value of the quantum yield of sodium salicylate, but it is difficult to say how reliable these measurements are. For λ 2537 Å at the optimum layer thickness, the quantum yield was 70% (ref. 56), and according to Nygaard's measurements, about 40% (ref. 58). The value of the quantum yield of this luminophor may be evaluated indirectly from the following data: Melhuish (ref. 59) measured the quantum yield of a series of substances including anthracene, and in the work of Watanabe and Inn (ref. 51) it was shown that the photocurrents observed in a study of the luminescence of anthracene and sodium salicylate differ only slightly; from each other and, since the regions of luminescence of the two phosphors coincide, the quantum yields should also coincide (about 20% for both phosphors). In the work of Chang (ref. 60) the quantum yield of sodium salicylate was taken to be 10%; after an accurate determination of the quantum yields of a series of luminophors (ref. 59) by means of comparative measurements, the quantum yield of other luminophors can be readily found (ref. 60). Strange as it may seem, despite the use of sodium salicylate, in the overwhelming majority of studies where the vacuum ultraviolet was recorded by means of the luminescence of luminophors, no reliable data are given for its quantum /2103 yield. This may be due to the fact that the quantum yield of the phosphor does not have to be known for absolute measurements, since the entire system as

a whole (phosphor + photomultiplier) is usually calibrated. The quantum yield of sodium salicylate is greater than that of many other phosphors (refs. 50, 53, 54). However, contrary to the erroneous statement by Krokowsky (ref. 61), no one has shown that it is close to unity. Lumogen has certain advantages over this luminophor because its sensitivity extends up to 4600 Å (ref. 62). In the shortwave region, terphenyl (ref. 56) has a higher quantum yield than sodium salicylate (ref. 56).

Heterochromatic photometry by means of luminophors having a constant quantum yield is extremely simple, since it amounts to comparing radiations of a constant spectral composition, and for this reason the spectral characteristics of the PEM do not have to be known. In choosing a photomultiplier, a PEM with maximum sensitivity in the region of luminescence of the phosphor is desired.

In order to perform absolute measurements, the photomultiplier is calibrated by comparison with a thermocouple. The calibration method is based on comparing the thermocurrents and photocurrents (refs. 50, 63). Unfortunately, when the calibration is carried out by this method, many sources of error arise: (1) inaccuracy in the calibration of the thermocouple itself, (2) irregularity in the operation of the photomultiplier, and (3) change in the properties of the luminophor. When absolute measurements are made, the quantum yield of the entire system as a whole (photomultiplier + luminophor layer) is determined. Photomultipliers can be calibrated not only with a thermocouple but also by using photochemical reactions (refs. 64, 65). It is convenient to carry out the calibration by means of the reaction of formation of ozone under the influence of the resonance radiation of mercury (λ 2537 Å); in measurements of high light fluxes capable of inducing a photochemical reaction, it is

necessary to decrease the sensitivity of the photomultiplier and operate at low voltages. Knowing the dependence of the amplification factor on the voltage, one can measure considerably weaker light fluxes than those which cause chemical reactions (the attenuation may amount to a factor of 10^7).

An important disadvantage of close-type photomultipliers is their sensitivity to radiation in the visible and near ultraviolet. In this case, it is much more expedient to use open-type photomultipliers (refs. 49, 63, 66-71), which are termed "blind to the sun." They have the advantage of being highly sensitive in the spectral region $\lambda < 2000$ Å and virtually completely insensitive in the region above 2000 Å. This leads to a decrease in the errors due to the presence of scattered light. In recording radiation shorter than 1000 Å, a requirement of prime importance set for the detector is an abrupt decline in the spectral characteristic in the region from 2000 to 1000 Å. One of the methods of attenuating the longwave radiation is the method of electric control of the spectral characteristic of the photomultiplier (ref. 72). To this end, a negative potential is applied to a grid located in front of the cathode. The grid stops slow photoelectrons. Another method, that of filters, may find applications (ref. 73). The filters used may be thin metallic films (of the order of a few tenths of a micron) of Al, Sn, In, Bi, Au, Ag, Cd (ref. 74). The transmission coefficient of these filters decreases abruptly for wavelengths above 1200 Å. In each case, a filter can be selected which in combination with a suitably chosen photocathode permits the recording of radiation in a relatively narrow spectral interval. These filters may find applications in the recording of radiation without a spectral instrument (see /2104 below). The operation of open-type photomultipliers is based on the existence of a bulk photoelectric effect whose influence is stronger than that of the

ordinary surface effect. What is very important is the fact that the bulk photo-electric photoeffect is independent of the state of the cathode surface (ref. 49). Pure metals, W, Pt, Ni, Au, can be used as the cathode. The quantum yield of pure metals in the region of 1000 Å is of the order of 0.1 electron/quantum (refs. 72, 75, 76), i.e., is much greater than the quantum yield in the region of the near ultraviolet (10^{-3}-10^{-5} electron/quantum). In many photomultipliers, use is made of composite photocathodes with a quantum yield no lower than that of pure metals. The photocathodes used are Cu-I, Cs-Te, Cs-Sb, Rb-Te, Cs-I (ref. 68), BeO, MgO, S_2F_2, Cs-I and a series of other materials (refs. 69, 70). In the soft X-ray region, photomultipliers from Cs-I and Sr-F$_2$ are particularly effective (refs. 77, 78), and their quantum yield attains several dozen per-cent. When these photomultipliers are used, the recording of the photocurrents is done in most cases by counting the pulses from individual photoelectrons (ref. 78). In a correct operating method, the efficiency of open-type photo-multipliers is determined by the value of the quantum yield of the external photoeffect of the photocathode.

In order to carry out relative measurements, one must know the dependence of the quantum yield of the photocathode on the wavelength. Such data can be obtained by a comparison with a nonselective detector (e.g., a thermocouple). An open-type photomultiplier can also be calibrated by comparing it with a closed-type photomultiplier; steps must be taken to exclude the access of scattered light.

Electron multipliers with magnetic focusing are used to record short ultraviolet radiation. Their characteristic feature is that a continuous strip of a high-resistance semiconducting material is used as the dynode. A de-scription of these photomultipliers can be found (ref. 49, 79-81). Fig. 12
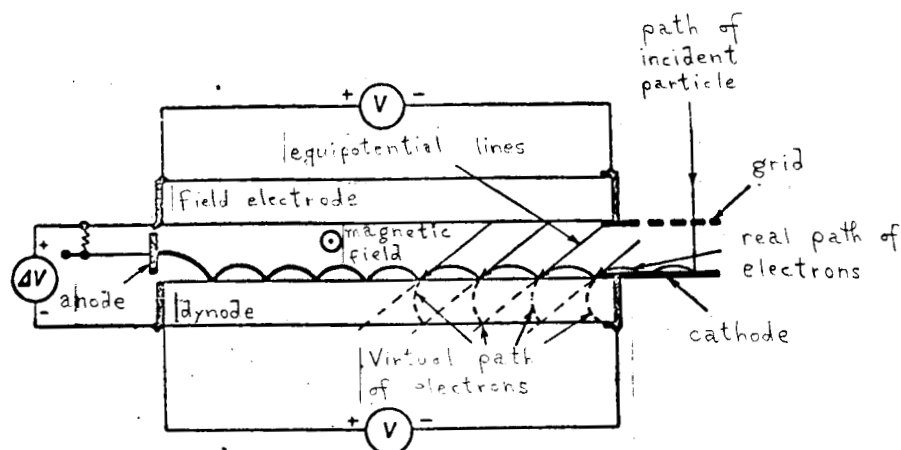
Figure 12. Circuit of photomultiplier with magnetic focusing.

shows a diagram of the operation of the instrument. The multiplier consists of

two strips having a high resistance; the distance between them is only a few

milimeters. Light passing through the grid strikes the cathode, which is a

continuation of the dynode strip. The magnetic field is perpendicular to the

plane of the figure (~300 gs). The same photential difference (~1500-2000 V)

is applied across the ends of the electrodes. In addition, a potential which is

positive relative to the lower electrode is applied to the upper electrode. The

direction of the equipotential surfaces is shown in Fig. 12. The electrons move

in a cycloid and strike the dynode without passing through its full loop. The

voltages are selected so that the coefficient of secondary emission is greater

than unity. The electron beam is collected at the anode (a ten-cascade photo-

multiplier is shown in the figure). The amplification factor along the dynode

strip changes with the applied voltage. As the voltage increases from 1000 to

2000, the amplification factor increases from 10^5 to 10^9 - fold (ref. 79).

Special experiments were carried out to compare the sensitivities of these

photomultipliers coated with alluminophor for the spectral region below and

above 1050 Å. Conditions were selected for which the signals measured by both

32

photomultipliers in the shortwave region were the same. Under these conditions

is was found that the signal for radiation longer than 1050 Å in the PEM with

magnetic focusing was 100 times smaller than in the closed-type PEM. There

lies the overwhelming advantage of the above-described photomultipliers, since

it permits one to disregard scattered light for λ>1000 Å. Concerning further

improvements of photomultipliers with magnetic focusing see the review of

Hinteregger (ref. 49).

A new detector of vacuum ultraviolet radiation was proposed by Lincke and

Wilkerson (ref. 82). It is called the PS (photoemission - scintillation)

detector (Fig. 13). The radiation strikes at an angle of 45° to the surface of

the gold cathode. The cathode is at a potential of 15 kV relative to the

grounded chamber. The photoelectrons leaving the gold cathode are accelerated

along the direction toward the scintillator, whose thickness is 3.2 mm. The

emitted light passes through the window of the photomultiplier and is recorded

in the usual manner. A thin aluminum film is applied on the scintillator;

this film absorbs scattered visible light and does not allow a negative charge

to build up on the scintillator, so that the energy loss of electrons passing

through the film is small. These detectors can be used to record radiation

shorter than 1300 Å.

A comparison of a PS detector with a sodium salicylate detector shows that

below 900 Å a PS detector is more sensitive and above 1000 Å, less sensitive.

The relative sensitivity of both detectors changes because of the change in the
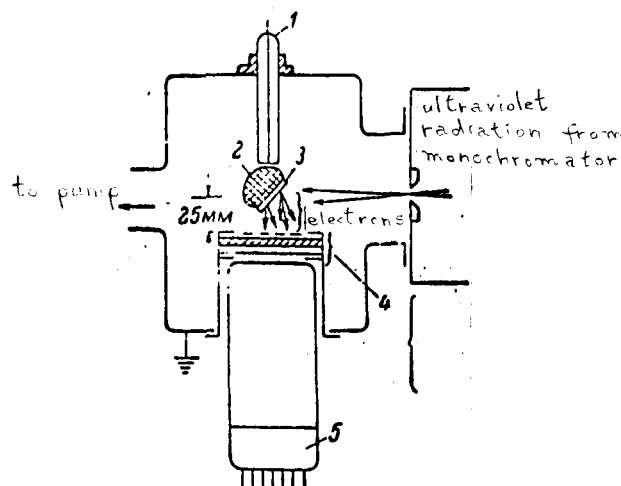
quantum yield of gold.

Figure 13. PS detectors.

Thermophosphors

Certain phosphors have the property of building up energy under the
influence of radiation. This energy is stored for a long time and can be
rapidly released as radiation when the temperature is raised. One of the
most commonly used thermophosphors is $CaSO_4$-Mn (refs. 83, 84).[1] Under the
influence of radiation shorter than 1500 Å, a green thermoluminescence is
observed (radiation maximum around 5000 Å). Fig. 14 shows the spectral char-
acteristic of the thermophosphor; the sensitivity maximum coincides with a
wavelength of about 1030 Å. The energy accumulated by the phosphor during
irradiation is released on heating to 180° C. For the same spectral composition
of the exiting radiation, the number of light quanta radiated by the phosphor on
heating is directly porportional to the number of light quanta striking it

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[1]The method of its preparation is extremely simple and has been described by
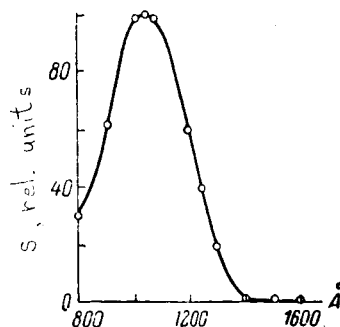Watanabe et al. (ref. 83).

34

Figure 14. Spectral characteristic
of thermophosphor.

during the excitation. In order to determine the total energy accumulated by
the phosphor, the latter is heated, and the area bounded by the thermolumines-
cence curve is measured (Fig. 15). The area is independent of the heating rate.
The released energy can be found by means of a storage circuit by measuring the
amount of electricity flowing through the PEM during the luminescence of the
phosphor (refs. 84, 85). Having the spectral characteristic of the thermophosphor,
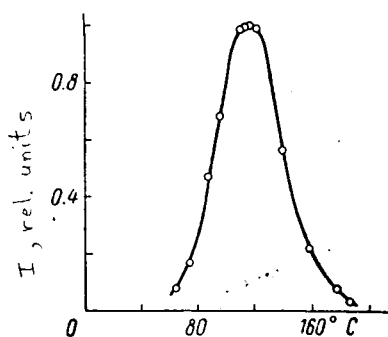one can compare two light fluxes of different spectral composition (refs. 83, 84).

Figure 15. Thermoluninescence
curve.

Apparently, the use of thermophosphors for these purposes is inexpedient,
since their spectral characteristic is very steep, and for this reason the

35

accuracy of the measurement is very low. Furthermore, only a very narrow
spectral interval can usually be measured with the aid of this phosphor; this
considerably restricts the applications of the phosphor to heterchromatic pho-
tometry. It is more convenient to use thermophosphors for absolute energy
measurements. One can thus measure with sufficient accuracy the radiation energy
corresponding to a given spectral line. Thus, for example, a thermophosphor was
used to measure the intensity of the helium 1215 Å line (ref. 46) in a con-
densed discharge; L_α was measured in many investigated upper layers of the
atmosphere (refs. 86, 87).

To carry out absolute measurements, the quantum yield of the phosphor must
be known, it depends appreciably on the method of preparation, the purity of
the starting materials and other properties; for this reason, it is necessary
to calibrate every freshly prepared phosphor. The calibration is performed by
comparison with a thermocouple. The quantum yield of the phosphor in the region
of maximum sensitivity may be 5-10% (ref. 83). The phosphor described in ref.
46 has a quantum yield of about 1% for λ 1216 Å.

Ionization detectors

The recording of a spectrum and the relative and absolute measurements made
by an ionization chamber are based on the fact that the incident quantum causes
the photo ionization of gas. Fig. 16 shows the ionization chamber used by
Watanable et al. (ref. 88). The chamber itself, having a diameter of 20 mm, and
the housing of the photomultiplier were placed in a metallic chamber attached to
the entrance slit. The chamber was closed with lithium fluoride windows; the
electrodes were made of platinum and were placed outside the light beam. The
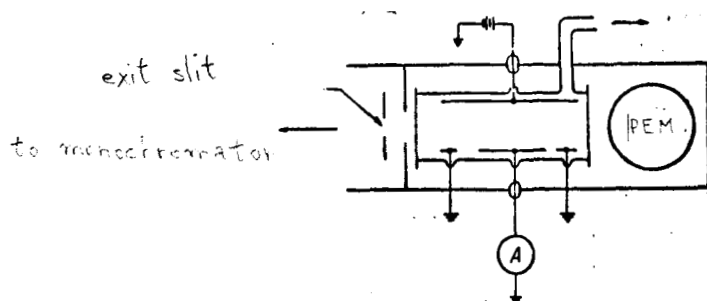length of the electrodes was about 4 cm. The potential difference created

Figure 16.   Circuit of ionization

chamber

between the electrodes was several volts, and the saturation current was reached

at only 4 V.   The magnitude of the ion current is a measure of the intensity of

the incident monochromatic radiation.   Knowing the absorption cross section and

photoionization quantum yield, one can find the intensity of the incident light

flux from the value of the ion current.   We shall introduce the following

symbols: 1 - length of ionization chamber; σ_1 - photoionization cross section;

σ - total absorption cross section; N_0 - total number of incident photons per

sec; N - total number of photons absorbed in 1 sec; N_1 - number of ion pairs

formed in the ionization chamber in 1 sec along the path 1 (determined from

measurements of the ion current); n_0 - number of molecules per unit volume.

On the basis of the Lambert-Beer law

$$N_0 = \frac{N}{1 - e^{-\sigma n_0 l}} \cdot$$ (12)

The value of N can be found by using the following formula

$$N = \frac{\sigma}{\sigma_1} N_1$$ (13)

σ/σ_1 characterizes the photoionization quantum yield of the gas filling the

chamber.   Thus, in order to perform relative measurements of intensity, one

must know the dependence of the absorption coefficient of the gas and quantum

37

yield on the wavelength. The only quantity subject to measurement is the ion current of the ionization chamber.

In absolute measurements, it is necessary to know the absolute value of the absorption coefficient of the gas as well as the absolute value of the photoionization quantum yield.

The first studies dealing with the measurement of radiation by means of a photoionization chamber were carried out with the aid of chambers filled with NO (refs. 88-90); many other gases can also be used to fill the chambers (refs. 48, 81-93). The ionization of NO is observed for wavelengths shorter than 1350 Å. The chamber filled with NO can be used to record L_α. For the spectral region from 1300 to 800 Å, the photoionization quantum yield of NO is constant (refs. 88-90). The photionization quantum yield of NO was refined and amounts to 80-85% (ref. 48). The determination of the photoionization quantum yield constitutes a very difficult experimental problem. As is clear from the above, an experimental determination of the ratio σ/σ_1 requires that N/N_1 be found; N_1 can be readily determined from measurements done with an ionization chamber. A curve is plotted which relates the ionization current with the voltage between the electrodes of the ionization chamber (Fig. 17); the ion current is determined form the value of the saturation current. To determine the number of absorbed photons (N), it is necessary to have a calibrated detector. The radiation detectors ordinarily used are photomultipliers calibrated with a thermocouple. The thermocouple is calibrated for the visible, and it is postulated that the calibration is valid in the vacuum region as well.

When a calibrated photomultiplier is available, to determine the photoionization quantum yield, it is necessary to perform absolute measurements of the intensity at the exit from the spectral instrument and after passage of the
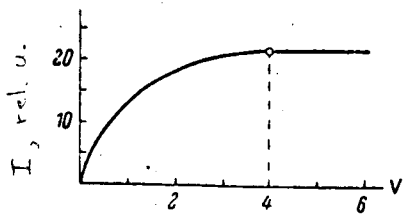
Figure 17. Current-voltage characteristic of the photoionization process.

radiation through the ionization chamber. These measurements are fairly complex and involve many sources of error, so that wherever possible it is better to use ionization chambers filled with monatomic gases.

As was verified by Samson (ref. 48) and in complete agreement with theoretical considerations, the photoionization quantum yield of inert gases, starting at the ionization threshold, is equal to unity and is independent of the wavelength. Using ionization chambers filled with inert gases, one can record wavelengths shorter than 1027 Å; to record wavelengths shorter than 1350 Å, the chambers were filled with nitrogen oxide, and to measure radiation of longer wavelengths, with xylene (ref. 94).

Geiger counters are beinning to be widely used for absolute measurements of intensities in the vacuum region of the spectrum (refs. 95-97). The calibration methods and details of the design of counters permitting absolute intensity measurements are described by Rumsh, Lukirskiy et al. (refs. 95, 96).

Photographic Plate and Other Photochemical Detectors

The recording of quanta and measurement of absolute and relative light intensities by means of photochemical reactions are two of the most accessible

39

photometric methods (ref. 65). It is no wonder that these methods began to be used as long ago as the last century. In the recording of the vacuum ultraviolet, a series of chemical reactions may be used: formation of ozone (refs. 98-100), decomposition of carbon dioxide (refs. 100-102), decomposition of ammonia (refs. 100, 101, 103). The quantum yield of all these reactions is known and is determined with a thermocouple. However, the absolute quantum yield of a chemical reaction is not a constant quantity, since the value of the quantum yield is affected by the reverse reaction. Thus, for example, for CO_2 the quantum yield varies from 0.98 to 1.9 (ref. 102); therefore, errors may be observed in the determination of the radiation intensity which reach 100% of the value being measured. Furthermore, the use of photochemical detectors is fairly cumbersome, since it involves chemical analyses. For this reason, the measurement of absolute intensities by means of chemical reactions is not used very much and is suitable only for approximate estimates. Thus, for example, this method may be used to evaluate the intensity of light sources under development (refs. 99, 102) or to compare various light sources with one another.

Photochemical reactions are suitable for purposes of heterochromatic photometry, since the quantum yield of chemical reactions remains constant over wide spectral intervals as the wavelength changes.

The use of photoemulsions is also based on a chemical reaction induced by light. For relative intensity measurements in the vacuum region of the spectrum, the photographic plate is sensitized with a luminophor of constant quantum yield (see section 1, 7) and the problem of heterochromic photometry is thus reduced to a problem of homochromic photometry.

In absolute intensity measurements, it is necessary to determine the radiation energies to which definite blackenings on the photoemulsion correspond.

40

However, the magnitudes of blackening of the photoemulsion depend on all sorts of secondary factory which are difficult to take into account, and for this reason the use of such methods is possible in practice only when the photographs of the spectral of the unknown and standard radiation are developed simultaneously. Any preliminary calibration of the photoemulsion leads to significant errors.

8. Mondispersion Methods of Measuring Extreme Ultraviolet Radiation

Up to this point we have discussed methods of measurement requiring the use of spectral instruments. Early in the 1950's, in the recording of undecomposed radiation, rocket investigations made wide use of counters and ionization chambers which made it possible to separate a relatively narrow region of the spectrum.

The ionization chambers are filled with a gas whose ionization potential determines the longwave limit of the recorded radiation. The lower limit of the recorded radiation is determined by the transmission of the window material. A gas whose function is to decrease or completely suppress the photoelectric effect at the cathode is usually introduced into the ionization chambers (or counters).[1] The gas must be electronegative (I_2, Cl_2, Br_2, NO); its presence markedly increases the work function of the cathode metal, and for this reason, the ionization chamber is sensitive only to radiation capable of causing the photoionization of

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[1] All that will follow is equally applicable to counters and ionization chambers, since the transition from the counting mode to the operational mode of the ionization chamber depends solely on the voltage applied. The optical characteristics remain the same.

41

the gas. In some cases, the absence of the photoeffect at the cathode is achieved simply by preventing the light from striking the photocathode.

We shall cite a table characterizing the ionization chambers in use (refs. 71, 94, 104).

Gas filling the chamber	Chemical composition	Window material	Region of sensitivity, Å	Quantum yield
Ethylene oxide	$(CH_2)_2O$	LiF	1050-1180	0.10-0.20
Carbon disulfide	CS_2	LiF	1050-1240	0.50-0.60
Acetone	CH_3COCH_3	CaF_2	1230-1290	0.08-0.10
Nitrogen oxide	NO	CaF_2	1230-1350	0.20-0.30
Nitrogen oxide	NO	LiF	1050-1350	0.30-0.40
Diethyl sulfide	$(C_2H_5)_2S$	BaF_2	1350-1480	0.10-0.20
Xylene	$C_6H_4(CH_3)_2$	Saphire	1425-1500	-
Iodine vapor	I_2	LiF	1050-1260	-

Note. In calculating the quantum yield, the quantum yield for NO at 1216 Å is taken to be 81%; the thickness of the window is 1 mm; the quantum yield is taken from ref. 104. The transmission of the window has been taken into account in the quantum yield column.

Knowing the ionization potentials of atoms and molecules (refs. 91, 92) and the transmission limits of various materials, one can select ionization chambers for other regions of the spectrum as well. In the region between 1000 and 100 Å there are no materials which are sufficiently transparent in thick layers, but thin layers of aluminum oxide, nitrocelluloid film, and SiO have been found to be transparent in thicknesses of hundreds and thousands of Ångstroms. Their extreme brittleness has not permitted the use of these films in rocket counters, but they

can apparently find applications under laboratory conditions. Ionization

chambers are most frequently filled with NO (ref. 105) and I_2 (refs. 106, 107).

Both of these gases do not react chemically with the material of the counter,

are electronegative, and have a high absorption coefficient. The quantum yield

of NO is 81-85% (ref. 48), and that of I_2, 40% (ref. 106). As is evident from

the table, the transmission bands of both counters are sufficiently narrow, but

a still greater monochromatization is needed in many cases for the recording of

individual lines. This is accomplished by using gas filters (see, for example,

ref. 105)). The "oxygen filter" is widely used (ref. 106). A cell 2 cm long

having lithium fluoride windows is filled with oxygen at atmospheric pressure.

Oxygen has a high absorption coefficient in the wavelength range from 1050 to

1750 Å (ref. 108), but in this region of the spectrum there are seven narrow

transmission bands, in one of which L_α is located. Therefore, ionization

chambers filled with NO or iodine vapor in combination with an oxygen filter will

make it possible to separate L_α with a sufficient degree of monochromaticity.

Counters can also be used to record radiation of longer wavelengths, but to

our knowledge, the operation of counters now in existence is not based on photo-

ionization, but on photoemission from the material of the cathodes. In partic-

ular, a chamber filled with a mixture of ethylene and argon was used for rec-

ordings in the region from 1725 to 2100 Å; the pressure of each gas was 10 mm Hg.

The cathode was made of a chromium-iron alloy (ref. 101).

To record radiation below 1050 Å, use can be made of open photon counters

(refs. 94, 110). Light passes through an aperture of small diameter (about 0.1

mm), and the pressure in the chamber in the counter decreases slowly and is

kept constant by means of a jet. Inert gases are used to fill the counters.

When the chamber is filled with ehlium, radiation shorter than 507 Å is recorded;

when neon is used, the recorded radiation is shorter than 577 Å, and is shorter than 791, 890, and 1027 Å for argon, crypton, and xenon, respectively. The consecutive use of counters filled with various gases permits the measurement of the light flux intensity in very narrow spectral intervals. The use of ionization chambers filled with an inert gas is convenient, since the quantum yield of these gases is constant and equal to unity (ref. 48).

A counter or ionization chamber is used to record radiation without spectral decomposition in two cases: first, to measure energy released within a definite spectral interval, and second, to record a single spectral line. The latter procedure is possible if only one spectral line falls into the region selected by the counter either with or without a filter. If the counter measures only one spectral line, its absolute intensity may be determined with sufficient reliability by calibrating the ionization chamber with a thermocouple or by any other method.

In the measurement of the energy within a given spectral interval, absolute measurements cannot claim a high degree of accuracy, since the quantum yield of the counter is not a constant quantity because of the change in the transmission coefficient of the window within the spectral region selected by the counter.

To record a spectrum without spectral decomposition, not only counters but thermosphosphors are used. Thus, for example, the thermophosphor $CaSO_4$-Mn was used to record the short ultraviolet radiation of the sun (ref. 87). The measurements were made with the aid of filters: a CaF_2 filter selected the region of 1230-1340 Å, the LiF filter - the region of 1040-1340 Å, Be - the region of 0-8 Å, and the region 0-1340 Å was selected without a filter; by combining the filters, radiation within various spectral intervals could be recorded. These measurements could not claim a high degree of accuracy, since

the spectral sensitivity of the phosphor and the transmission coefficient of the filter were not constant, but some idea of the distribution of solar energy in this region was obtained.

Conclusion

We have examined a whole series of methods of performing absolute and relative intensity measurements in the vacuum ultraviolet. The difficulties inherent in carrying out these measurements are based on a lack of standard sources for the calibration of the spectral instruments and radiation detectors. <u>/2111</u> Apparently, high hopes may be placed in the use of the synchrotron; the standard source could be any source with a constant spectral characteristic which could be calibrated with sufficient reliability by comparing it with the synchrotron radiation.

Until such "secondary standards" are created, the standard source can be used to calibrate the whole recording system at separate points only.

If it is desired to have a continuous calibration over the entire vacuum region of the spectrum, one must select another method, namely, the separate calibration of the spectral instrument and of the detector (ref. 36).

It is desirable to check one method by the other by performing the measurements of the same intensities by both methods. It should be noted that the method of calibrating the entire system as a whole is less accurate, but that it is much simpler, and thus the appearance of systematic errors is less probable.

Of the radiation detectors which we discussed, open photomultipliers and ionization chambers filled with inert gases appear to have unquestionable advantages over other detectors.

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